Evolution of topological defects in the early universe and its implications for physics beyond the standard model

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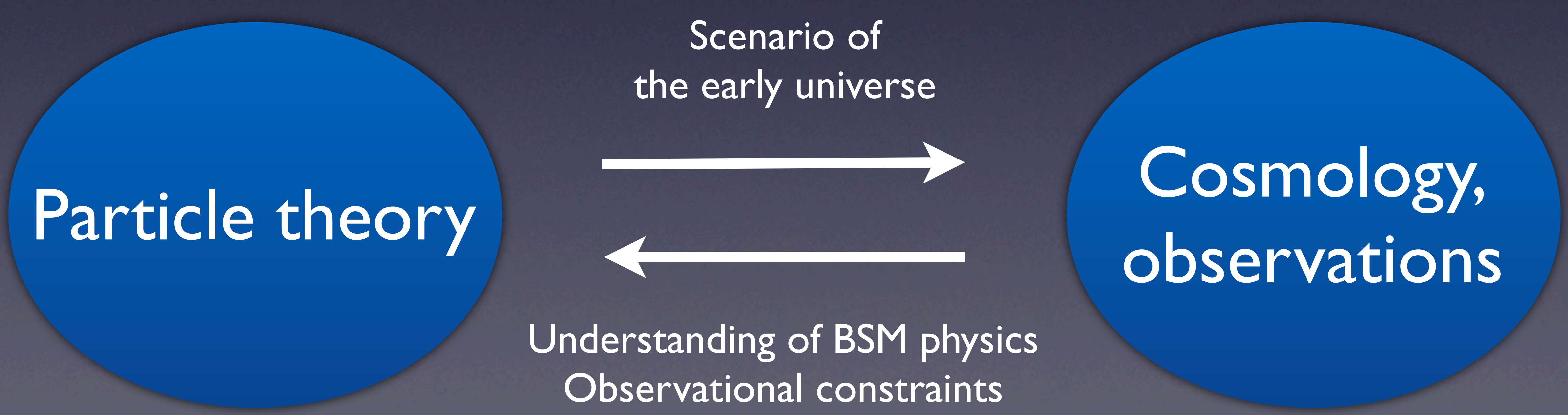
Research interest: particle cosmology

- Connection between cosmology and theory of fundamental physics
- Properties of particle physics models beyond the standard model (BSM) affect the early history of the universe
- Probe of very high energy physics, whose energy scale may not be accessed in collider experiments

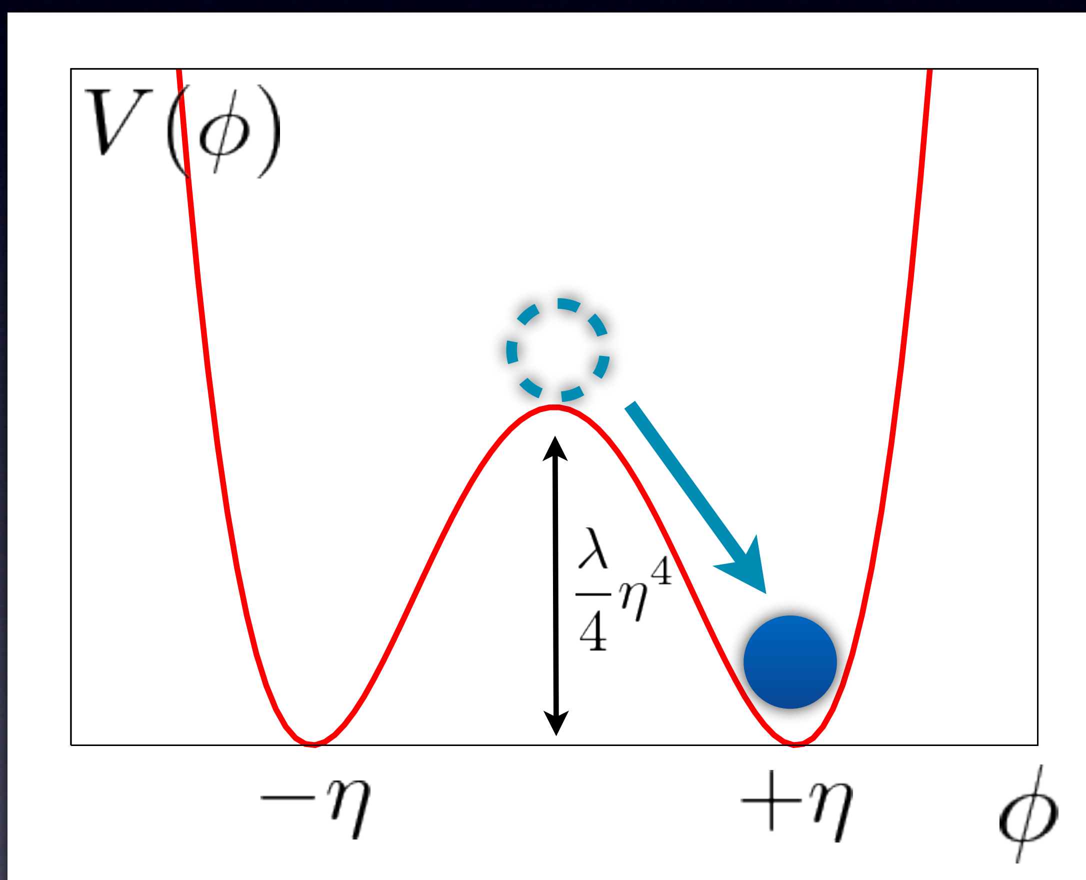


Topological defects

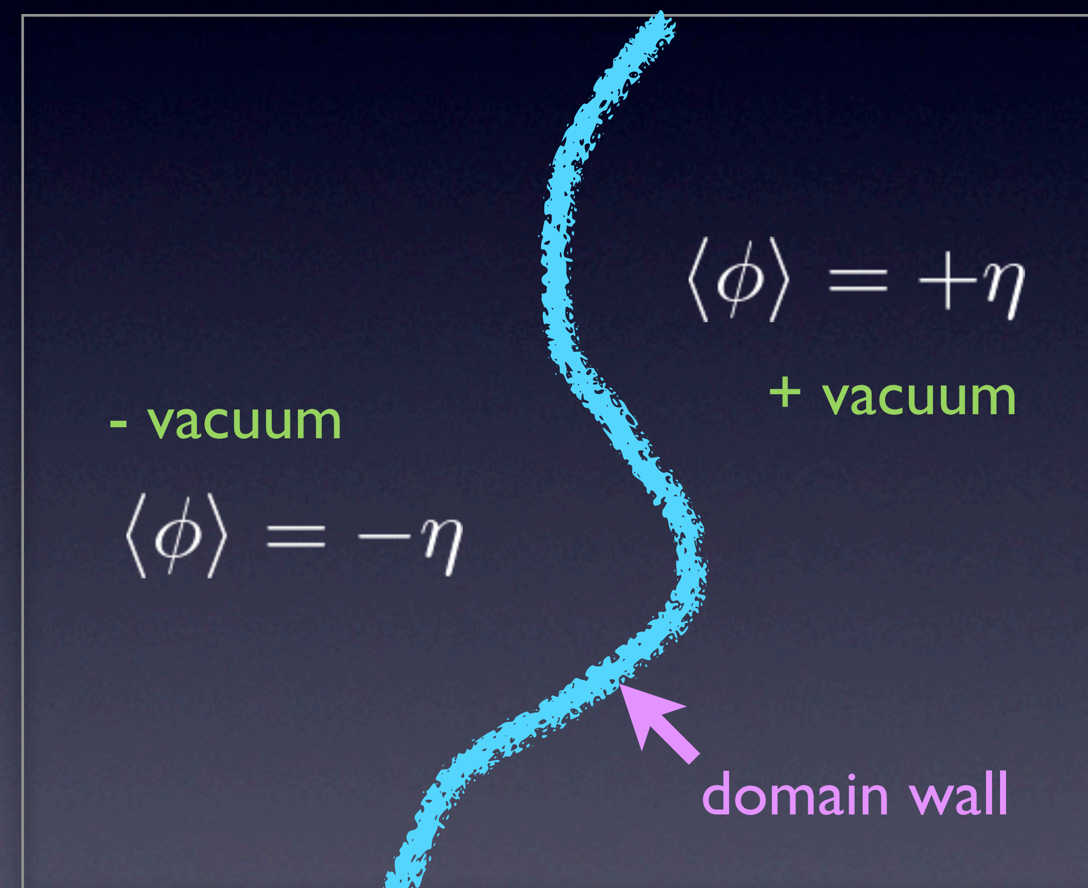
Some high energy physics models predict spontaneous symmetry breaking in the early universe, which leads to nontrivial field configurations

Example: $Z_2 \rightarrow 1$

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - \eta^2)^2$$



field space



coordinate space

Relics: particles produced from them, gravitational waves, etc.
→ can be considered to constrain the models

Study on topological defects

- Production of gravitational waves from domain walls

  Hiramatsu, Kawasaki, KS, JCAP05(2010)032 [1002.1555]
  Kawasaki, KS, JCAP09(2011)008 [1102.5628]
  Hiramatsu, Kawasaki, KS, JCAP02(2014)031 [1309.5001]

- Axion dark matter production from topological defects

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  Hiramatsu, Kawasaki, KS, Sekiguchi, PRD85, 105020 (2012) [1202.5851]
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  Kawasaki, KS, Sekiguchi, PRD91, 065014 (2015) [1412.0789]

- Domain walls in the next-to-minimal supersymmetric standard model (NMSSM)

  Kadota, Kawasaki, KS, JCAP10(2015)041 [1503.06998]
  Mazumdar, KS, Yamaguchi, Yokoyama (2015) [1511.01905]

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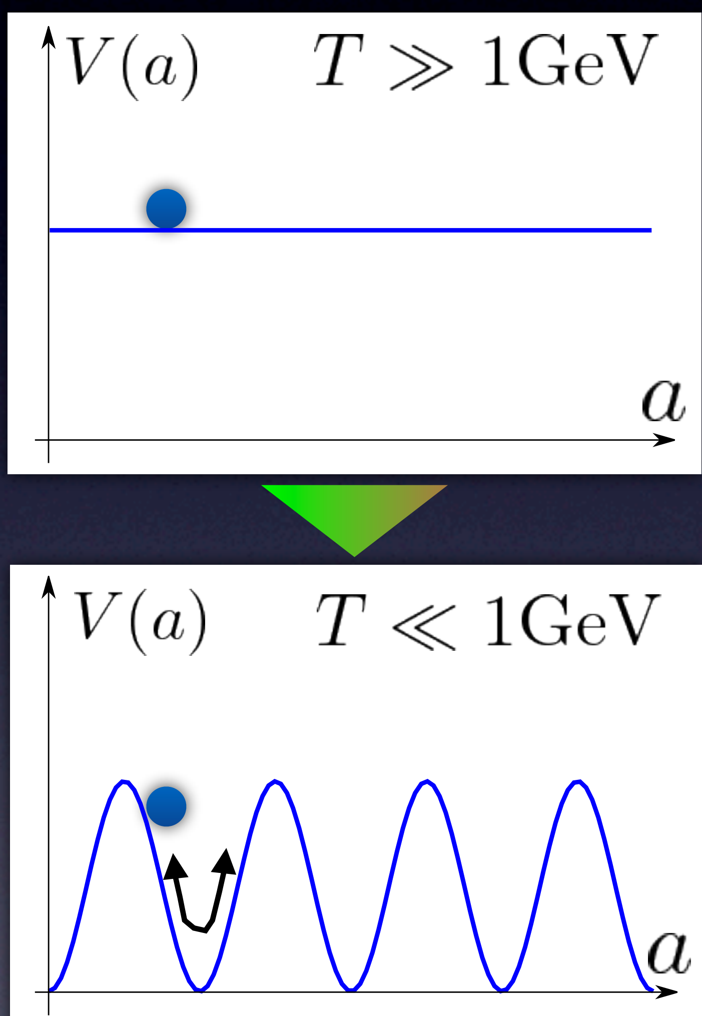
Axion cosmology

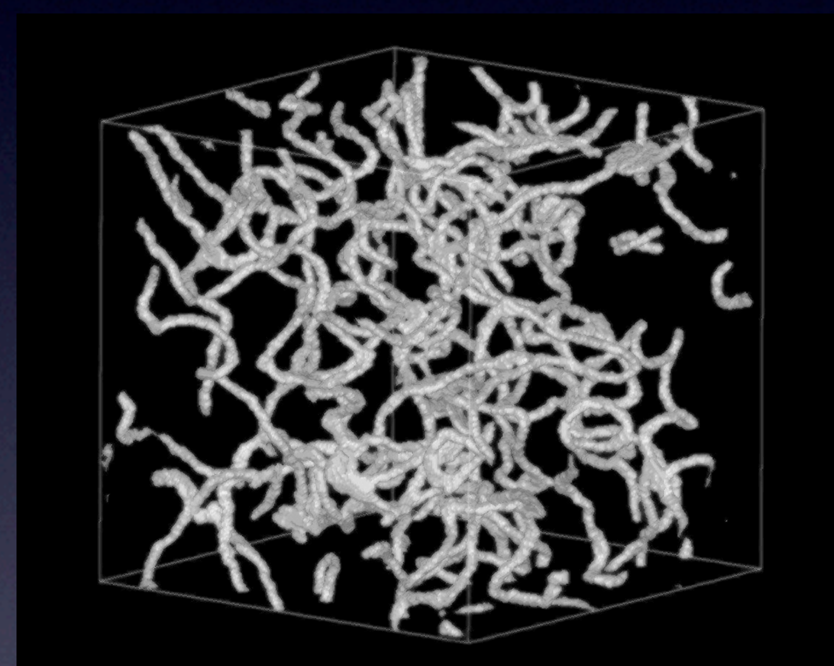
How axions are produced ?

Three mechanisms

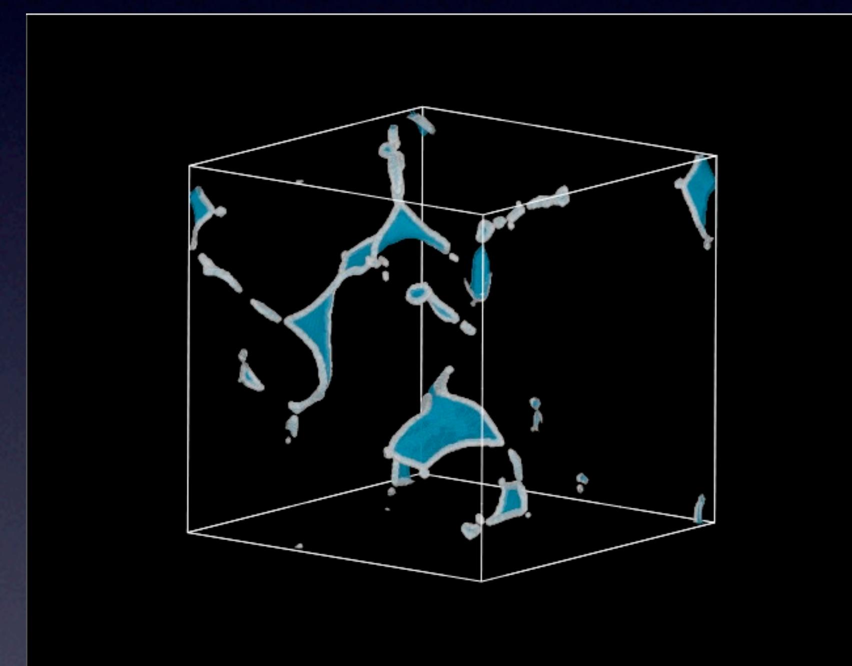
(1) misalignment mechanism



(2) radiation from strings



(3) radiation from string-wall systems



If Peccei-Quinn symmetry is broken after inflation, additional contributions (2) & (3) become relevant

Axionic string and axionic domain wall

Peccei-Quinn field (complex scalar field)

$$\Phi = |\Phi| e^{ia(x)/\eta}$$

$a(x)$: axion field

$$F_a = \eta / N_{\rm DW}$$

String formation $T \lesssim F_a$

Spontaneous breaking of $U(1)_{PQ}$

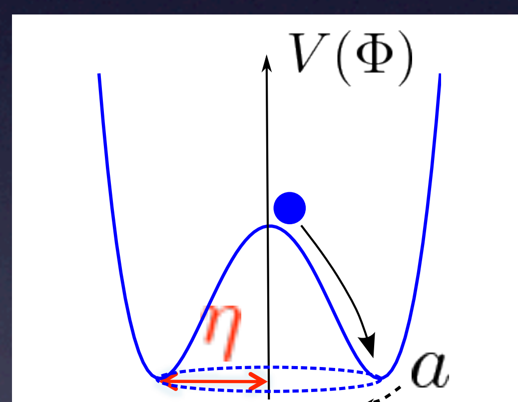
$$V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - \eta^2)^2$$

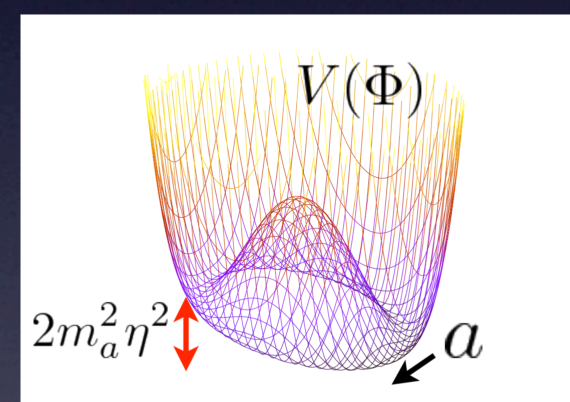
Domain wall formation $T \lesssim 1{\rm GeV}$

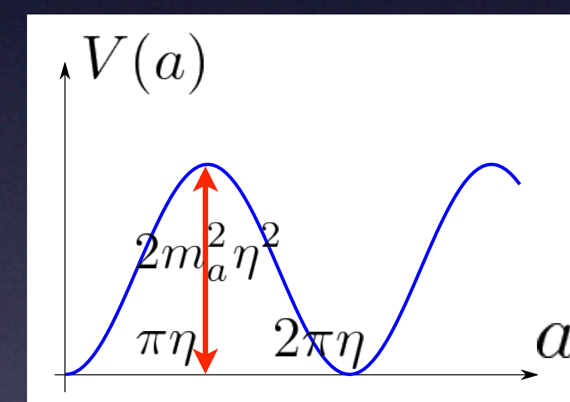
QCD effect

$$V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - \eta^2)^2 + m_a^2 \eta^2 (1 - \cos(a/\eta))$$

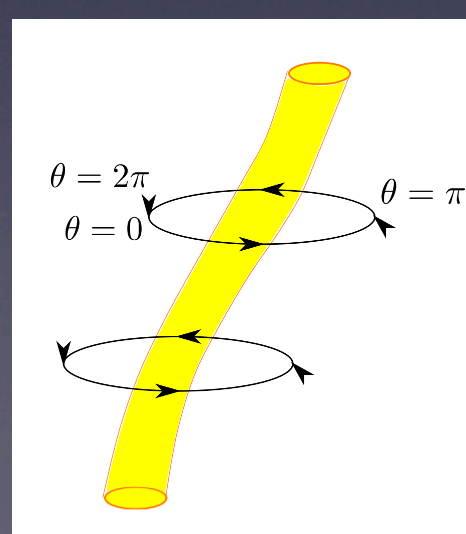
field space

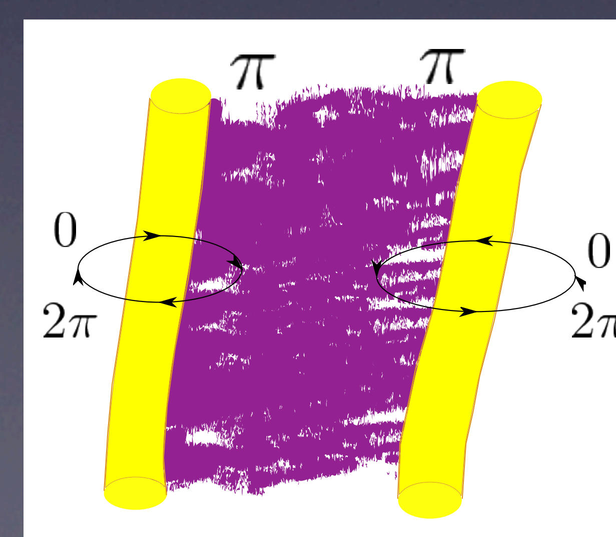






coordinate space



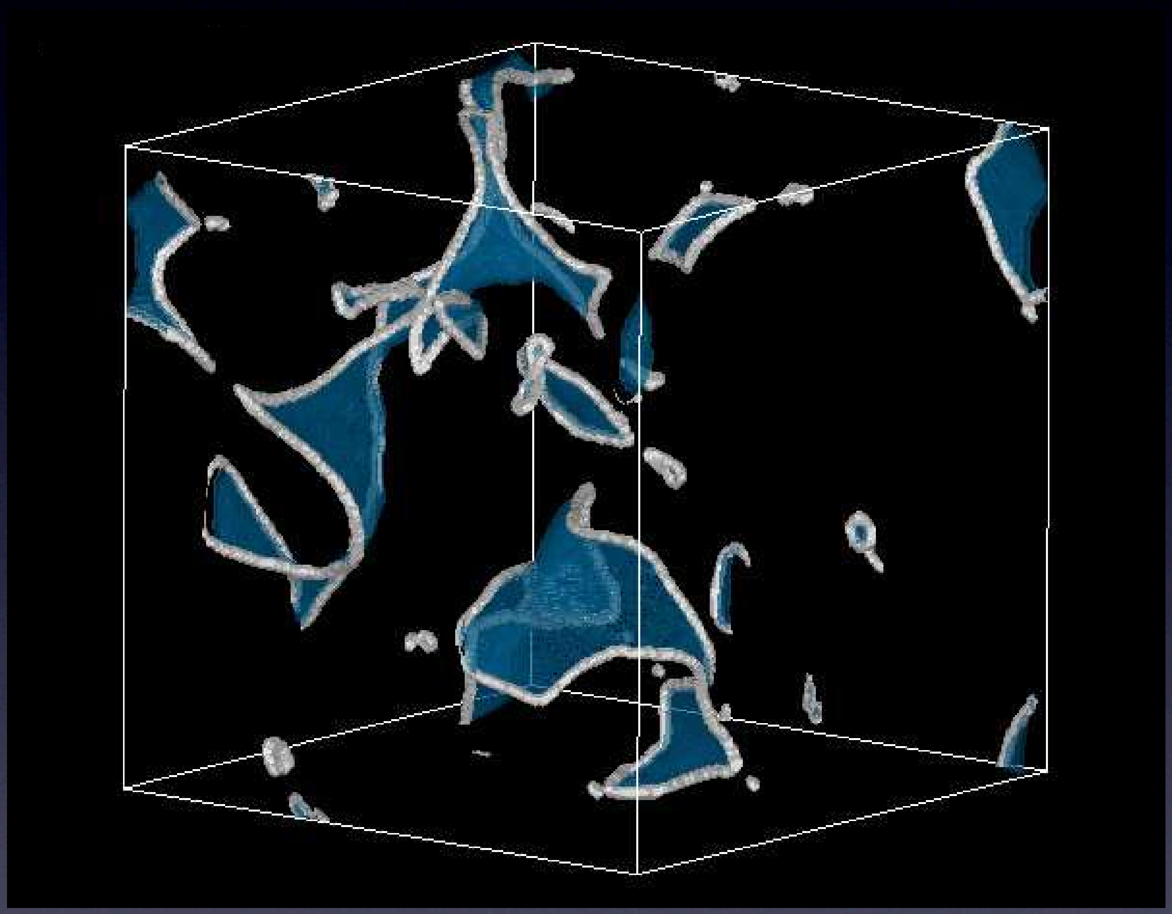


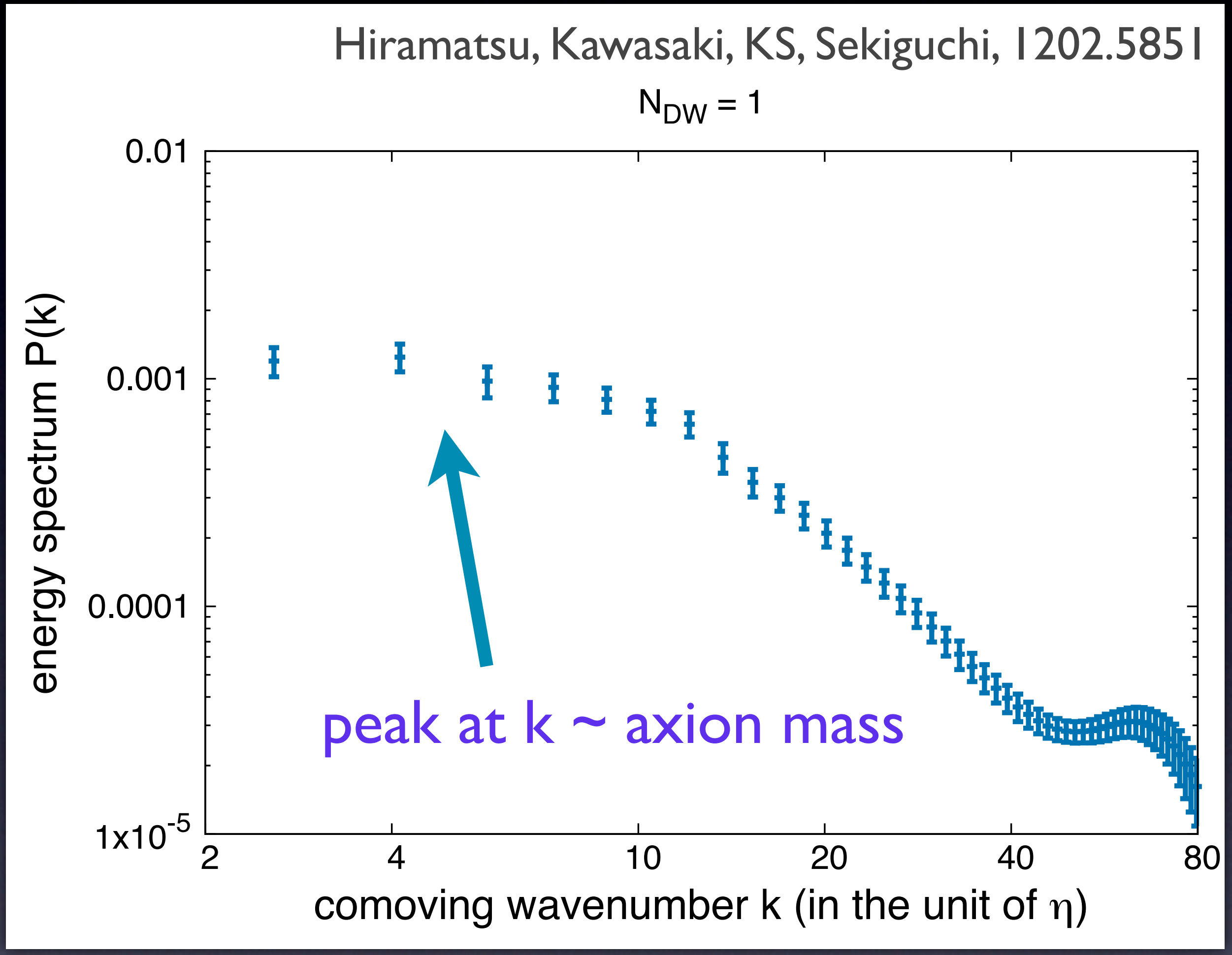
strings attached by domain walls

Numerical simulations

- Numerical simulation of domain walls bounded by strings
  → estimate energy spectrum of radiated axions

3D lattice with 512^3





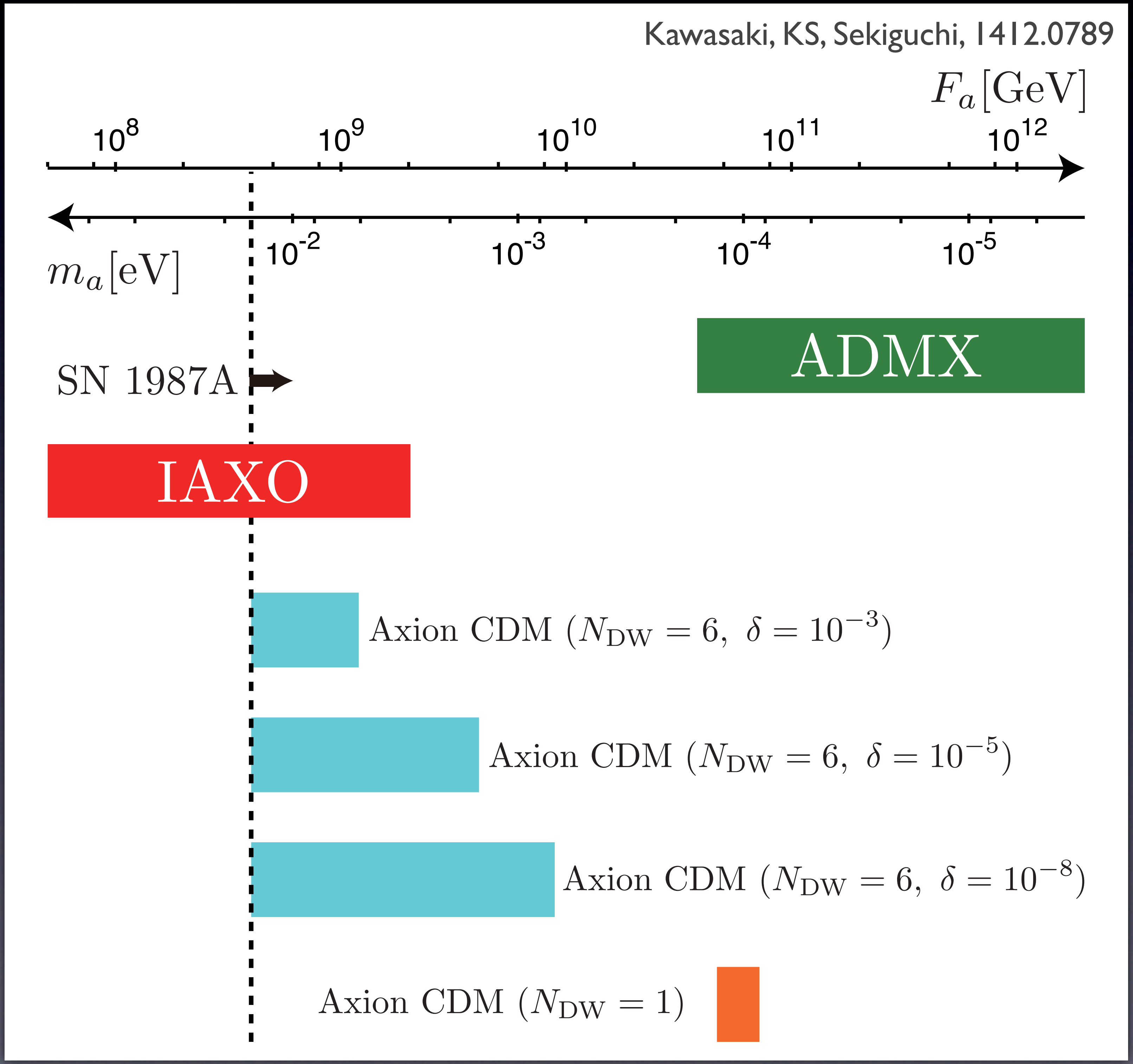
- Compute the total relic abundance of axions using the results of numerical simulations

- Axion density from decay of string wall systems is comparable to (or much larger than) axion densities from other sources

- Additional contribution from string-wall systems

  → axions can be CDM at low F_a (high m_a)

- It can be probed in the next generation experiments



Cosmological aspects of NMSSM

Next-to-minimal supersymmetric standard model (NMSSM)

- Additional singlet field S dynamically generates the μ term in MSSM

$$W_{\rm MSSM} \supset \mu H_u H_d \quad \Rightarrow \quad \lambda S H_u H_d + \kappa S^3$$

$$\boxed{\mu_{\rm eff} = \lambda \langle S \rangle}$$

- Theory possesses a discrete Z3 symmetry

$$\boxed{Z_3 : \ \Phi \to e^{2\pi i/3} \Phi}$$

$\Phi = (L, E^c, Q, U^c, D^c, H_u, H_d, S)$: every chiral supermultiplets of the NMSSM

- Z3 is spontaneously broken when S, H_u, H_d acquire VEVs

Formation of domain walls ?
How ? and under what conditions ?
We must carefully see the evolution of S in the early universe

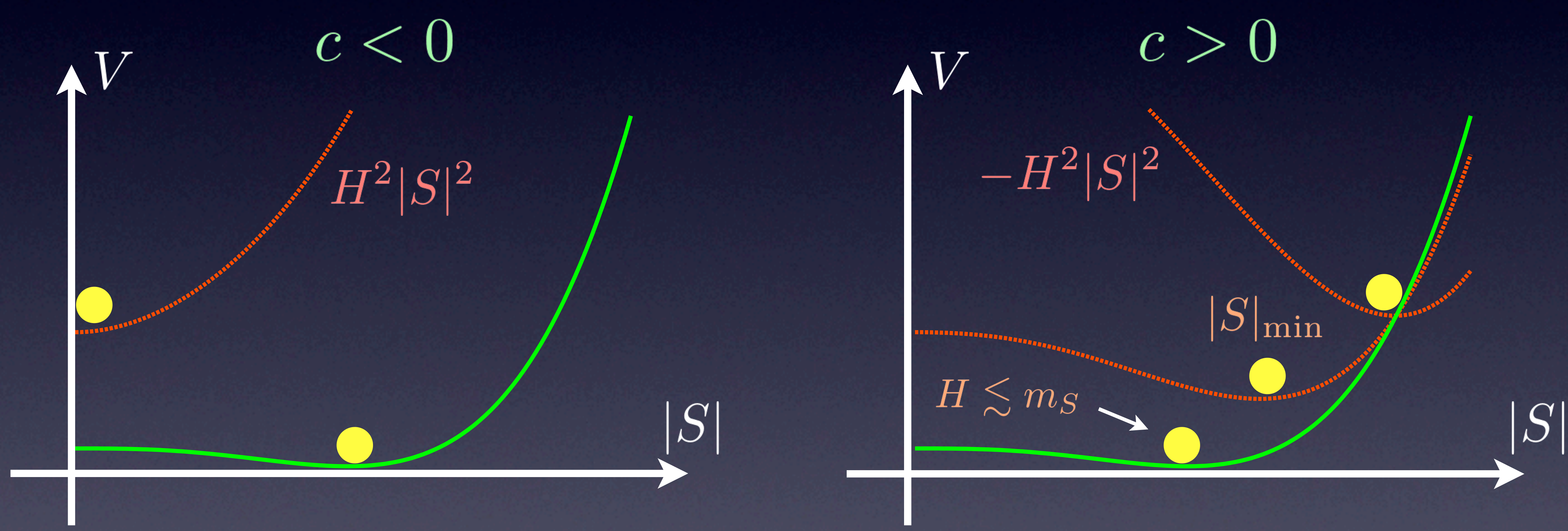
Evolution of singlet field in the inflationary universe

S can acquire an effective mass proportional to H

$$\mathcal{L} \supset \frac{|S|^2}{M_{\rm Pl}^2}\partial_\mu I^* \partial^\mu I, \ \frac{|S|^2}{M_{\rm Pl}^2} V(I) \quad \Rightarrow \quad \boxed{m_{S,\rm eff}^2 = -cH^2}$$

I : inflaton field

c : model-dependent parameter



If $c>0$, S may track minimum of the effective potential after inflation

⇒ a possibility to avoid the formation of domain walls

Conditions to avoid the domain wall formation

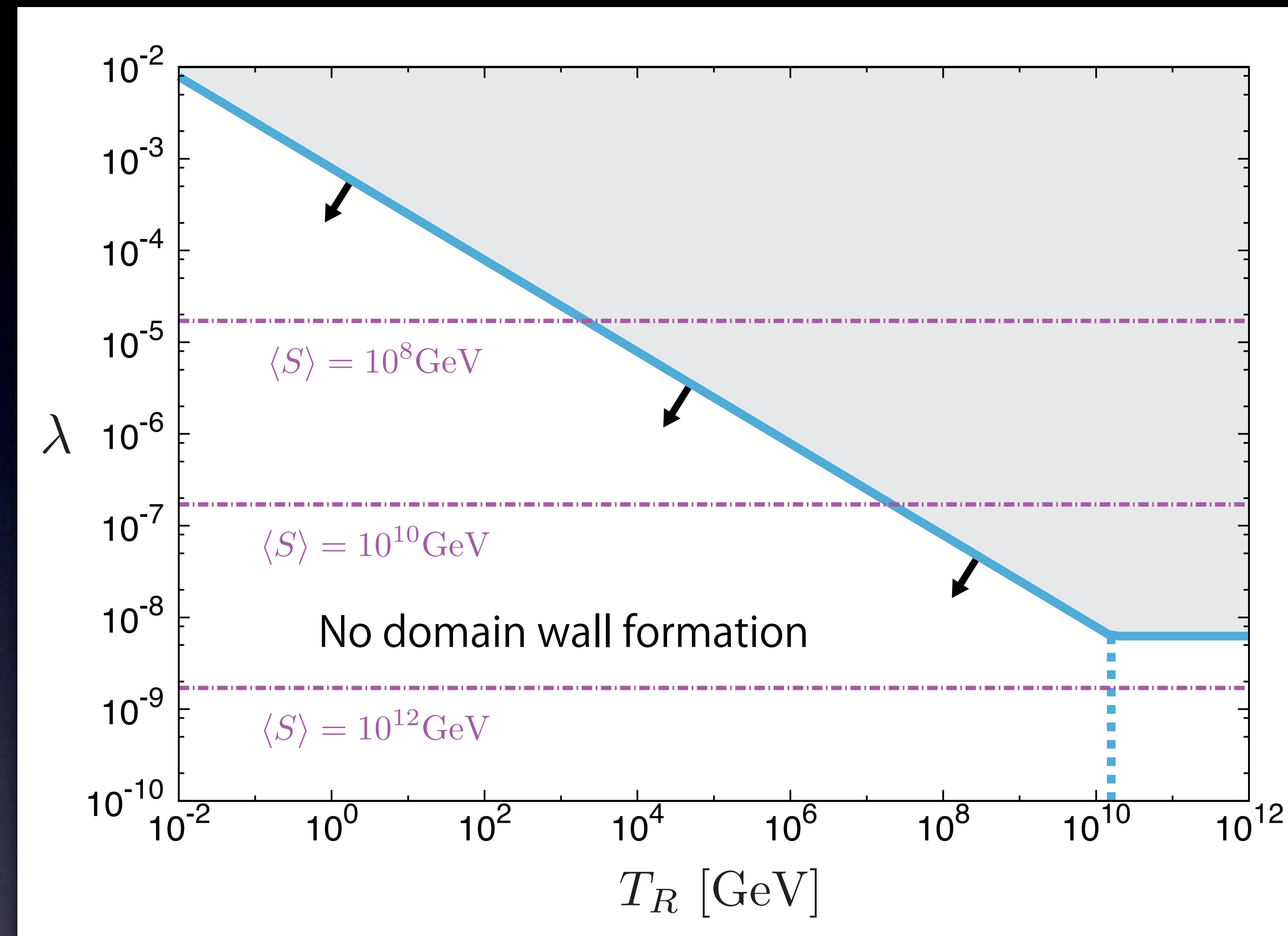
Mazumdar, KS, Yamaguchi, Yokoyama, 1511.01905

$$V(S) \simeq -cH^2|S|^2 - \left(\frac{\kappa}{3}c' H S^3 + \text{h.c.}\right) + \kappa^2|S|^4$$

TABLE I: Lower bounds on the coefficients of the Hubble induced corrections given by Eq. (18) for some choices of the energy scale of inflation $V_{\rm inf}^{1/4}$. Here we use the relation $H_{\rm inf}^2 = V_{\rm inf}/3M_{\rm Pl}^2$ and the value for the soft parameter $|A_\kappa| = 1\text{TeV}$.

$V_{\rm inf}^{1/4}$	$2\times 10^{12}\text{GeV}$	$2\times 10^{15}\text{GeV}$
$H_{\rm inf}$	10^6GeV	10^{12}GeV
$c,\ \tilde{c}$	$\gtrsim 100$	$\gtrsim 10^6$
$c',\ \tilde{c}'$	$\gtrsim 10$	$\gtrsim 10^3$

$$c \gtrsim \mathcal{O}\left(\frac{H_{\rm inf}}{|A_\kappa|}\right)^{2/3}, \quad c' \gtrsim \mathcal{O}\left(\frac{H_{\rm inf}}{|A_\kappa|}\right)^{1/3}$$



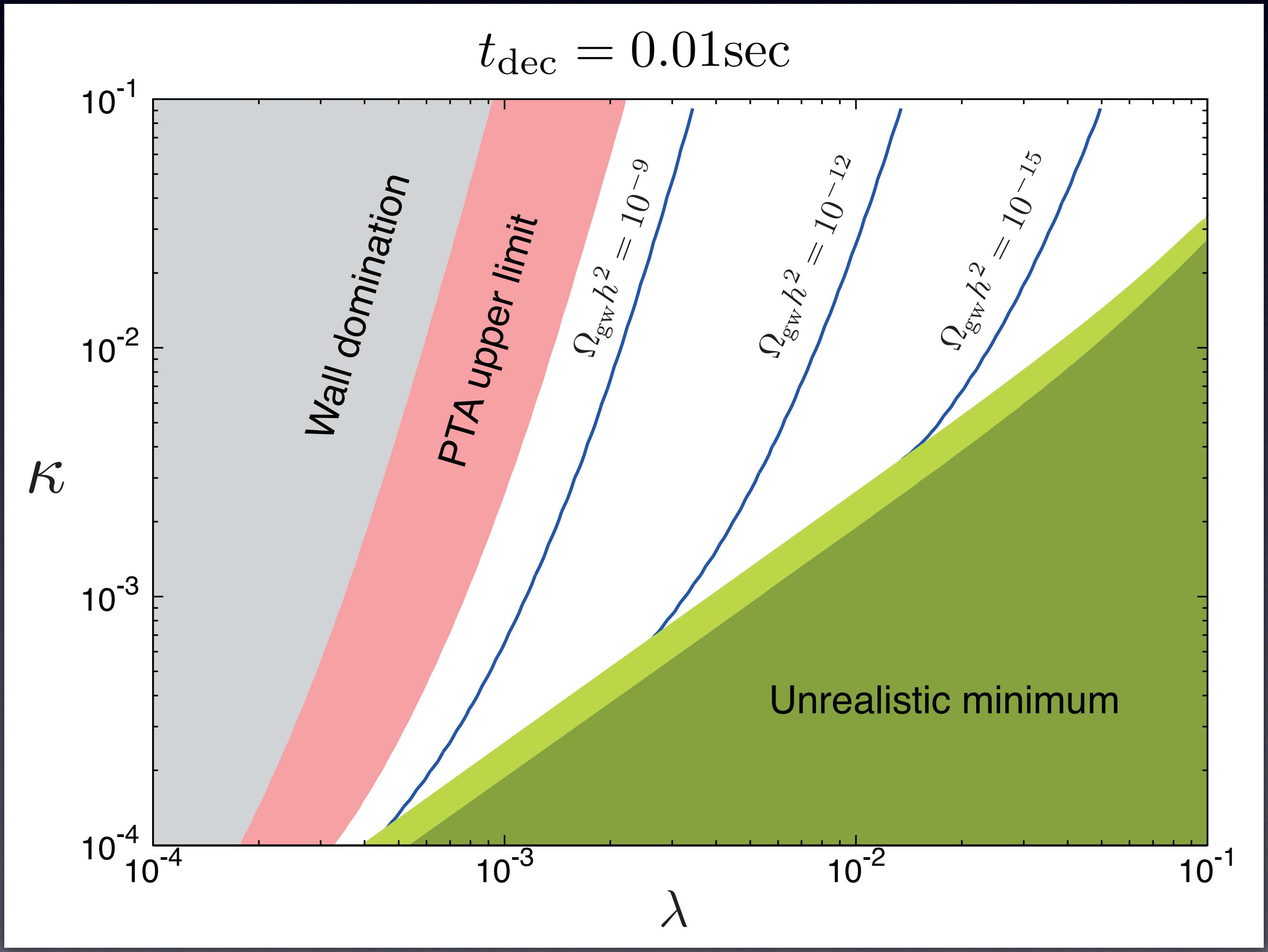
(assuming that $\lambda \simeq \kappa$)

- Large coefficients c , c', low reheating temperature T_R , and small Higgs-singlet coupling λ are required
- Otherwise we must take account of the formation of domain walls seriously

Gravitational waves from NMSSM domain walls

Kadota, Kawasaki, KS, 1503.06998

- Domain walls can collapse at some late time $t_{\rm dec}$ if the discrete Z_3 symmetry is only approximate (accidental)
- Signature of gravitational waves produced from long-lived domain walls is estimated



Summary

- Some early universe scenarios related to topological defects in BSM models are considered
- Axion cosmology:
  - If Peccei-Quinn symmetry is broken after inflation, radiations from string-wall systems give additional contributions to the CDM abundance
  - Mass ranges can be probed in the future experiments
- NMSSM cosmology:
  - Conditions to avoid the formation of domain walls are specified
  - If they are formed, they produce gravitational waves and future observations also constrain model parameters